Enabling role of hybrid simulation within the NEES infrastructure in advancing earthquake engineering practice and research

Daniel Gomez, Shirley J. Dyke, and Amin Maghareh

{dgomezp, sdyke, amaghare} @ purdue.edu

Report IISL – 008, December 2014

Intelligent Infrastructure Systems Laboratory

Abstract

Hybrid simulation is increasingly being recognized as a powerful emerging technique for laboratory testing. It offers the opportunity for global system evaluation of civil infrastructure systems subject to extreme dynamic loading, typically with a significant reduction in time and cost. In this approach, a reference structure/system is partitioned into two or more substructures. The portion of the structural system designated as 'physical' or 'experimental' is tested in the laboratory, while other portions are replaced with a computational model. Many projects have effectively used hybrid simulation (HS) and real-time hybrid simulation (RTHS) methods for examination and verification of existing and new design concepts and proposed structural systems or devices. This paper provides a detailed perspective of the enabling role that HS and RTHS methods have played in advancing the practice of earthquake engineering. Herein, our focus is on investigations related to earthquake engineering, those with curated data available in their entirety in the NEES Data Repository. (https://nees.org/). This report provides a discussion of several hybrid simulation (or RTHS) NEES projects in the recent years. These noteworthy projects have made use of hybrid simulation techniques to demonstrate and validate new design concepts and performing research focused on advancing civil engineering. These projects demonstrate that hybrid simulation offers a cost-effective alternative for better understanding of structures and components subject to extreme dynamic loads. Although hybrid testing has facilitated the completion of several high impact projects, the full power of this approach has yet to be unleashed.

Keywords: earthquake engineering; seismic experimentation; hybrid simulation; real-time hybrid simulation; design guideline; building code

Acknowledgement: This work was financially supported by the Colombia-Purdue Institute for Advanced Scientific Research (CPI), Universidad del Valle and Purdue University. The NEEShub (https://nees.org/) was established with funding from the US National Science Foundation (NSF) under Award Number CMMI-0927178. The authors also acknowledge the dedication of NEES researchers who published their data via the Network for Earthquake Engineering Simulation Data Repository. Project data and images contained herein are available through the NEEShub, supported by the NSF Network for Earthquake Engineering Simulation Research (NEESR) Program under Award Numbers: CMMI-724172, CMMI-0116005, CMMI-0829978, CMMI-0936633, CMMI-0530737, CMMI-0324277, CMMI-0420974, CMMI- 0530756.

Data presented herein is available for download in the NEEShub (https://nees.org/).

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Chapter 1

Background

Earthquakes are a major source of catastrophic natural disasters, often leading to loss of human life, civil structures and infrastructures. Excessive disturbances produced by base excitation in civil structures can damage structural and non-structural elements and cause discomfort to occupants. To advance our understanding of seismic resilience to such impacts, establish performance-based seismic design methods, develop new mitigation technologies, and enhance lifeline systems, several classes of experimental methods are used to simulate and evaluate structural behavior under extreme dynamic loading. These including quasi-static testing, shake table testing, effective force testing, and hybrid simulation (HS) methods, and each has pros and cons. In quasi-static tests, displacements (or loads) are applied at a slow rate. Quasi-static testing can readily be implemented on large civil structures, although it has two drawbacks. A predefined displacement history is required, and the effects of acceleration-dependent inertial forces and velocity-dependent damping forces are neglected. To bypass these issues, shake tables, or earthquake simulators, are widely available to evaluate the dynamic behavior of structures. Shake table testing is conducted in real time, typically enabling researchers to achieve quite realistic conditions. Researchers have used shake tables to evaluate critical issues such as collapse mechanisms, component failures, acceleration amplifications, residual displacements and post-earthquake capacities (Schellenberg and Mahin, 2006). However, very few shake tables in the world are capable of full-scale testing of civil structures, and due to the scale of the specimen such experiments, may be prohibitively expensive. Thus, evaluating the dynamic behavior of structures using shake table is usually limited to prototypes and often conducted for critical parts of a structure at the component level (Shing et al., 1996).

Advances in our ability to perform more complex computational simulations have also generated a need to validate the results, calibrating analytical models and developing new design guidelines. This need, and the desire to increase the size of our specimens for more realistic evaluations, increase the cost of testing, and sometimes exceed the capacity of our facilities. These objectives have driven the need to consider new methods of testing that combine physical experimentation with computational simulation, a class of experimentation known as hybrid simulation (HS). In HS, the experimental (or physical) portions of the structural system are tested in the laboratory, typically including the more complex components that are a focus of the investigation, while other portions of the structure are replaced with computational (or analytical) models which typically include the well-understood behaviors (see Fig. 1.1).

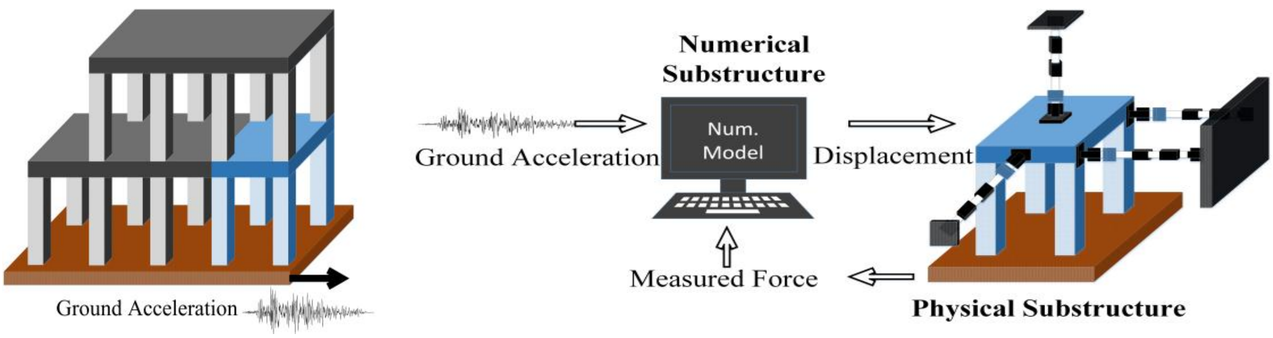


Figure 1.1: Concept of hybrid simulation

The concept of partitioning a reference system into numerical and experimental substructures originated in the field of aerospace and control engineering. Halbert et al. (1963) coupled digital and analog computers through a two-way data transfer system. In this study, adaptive path control of a two-dimensional maneuver under lunar attraction was simulated using HS. At each step, the digital computer performed a high-precision simulation of the rocket motion and sent its position and velocity to an analog computer. Then, the analog computer solved the corresponding boundary value problem and fed back the results to the digital computer (Halbert et al., 1963). Similarly, a HS of space vehicle guidance in a lunar landing was developed using a small digital computer tied to two fully-expanded analog computers (Heartz and Jones, 1966). In another noteworthy study using HS, Witsenhausen (1964) solved the equation of a chemical tubular reactor under various input conditions when a controller was installed.

Hybrid simulation found its way into structural engineering with Hakuno et al. (1969) who used HS to conduct a dynamic destructive test of a cantilever beam using an online system consisting of an analog computer and an electro-magnetic actuator. In this study, they developed an online computer-actuator system in an attempt to simulate earthquake responses of linear and nonlinear steel and concrete structures. To conduct HS, the floor displacement was computed using the numerical substructure (a nonlinear differential equation) and an actuator was used to apply the displacement to a one-story one-bay building frame (Takanashi et al., 1975).

Structural engineers evolved this approach into a new cost-effective experimental technique to evaluate the dynamic performance of large civil structures. In the late 80s, researchers had shown that results of HS and shake table tests are comparable if experimental errors are effectively mitigated (Takanashi and Nakashima, 1987, Mahin et al., 1989). When the structure under investigation (i.e. the reference structure) is divided into experimental and numerical substructures, coupling between the substructures is achieved by enforcing boundary conditions and equilibrium at the interface (Chen et al., 2012). One necessary assumption in HS is that the effect of loading rate on the interaction force of the numerical substructure is insignificant. Under certain conditions, this assumption has been validated for some structural materials, such as reinforced concrete and steel (Nakashima et al., 1992). The need to examine dynamic behavior and performance in rate-dependent structural components (e.g. rubber bearings, viscous dampers) combined with advances in embedded systems with hard real-time computing capabilities, have led researchers to conduct fast and real-time hybrid simulations (RTHS).

In recent years, HS and RTHS have played a noteworthy role in enabling new civil engineering concepts to be developed and validated under more realistic conditions, contributing to advance the practice of earthquake engineering around the world (Shao and Griffith, 2013). A large number of the projects employing HS and RTHS are published in their entirety in the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) Data Repository (at nees.org), where these data are open and accessible for use by other researchers (Pejša et al., 2014). Over the last decade, more than 400 research projects (https://nees.org/retrospective) have benefitted from an initiative funded by the US National Science Foundation (NSF) to build, maintain, operate and use the equipment facilities, interconnected via cyberinfrastructure, that comprise the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES). This unique infrastructure was managed first by the NEES Consortium Inc. (CMMI-0402490) for the period 2004-2009. Subsequently, the NEEScomm center at Purdue University managed the network for the period of 2009-2014 (CMMI-0927178). The NEES network, a "Laboratory without Walls", includes fourteen geographically-distributed, experimental earthquake engineering facilities, linked together with a robust, user-driven cyberinfrastructure which houses a curated, central data repository (Hacker et al., 2013). The NEES laboratories are equipped with unique large-scale equipment, such as geotechnical centrifuge centrifuges, tsunami simulation facilities, field testing equipment, shake tables, hydraulic actuators and strong walls (Ramirez, 2012). The cyberinfrastructure integrates an open repository for experimental/simulation data with simulation tools, national high performance computing resources, documents and educational resources (known as NEEShub).

The arrival of the NEEShub has ushered in a new collaborative capability with vastly improved information technology resources for research and education in earthquake engineering (Hacker et al., 2013). Researchers have taken advantage of this shared-use network of facilities connected with a unique cyberinfrastructure to accelerate progress in HS (Nakata et al. 2014, Christenson et al. 2014) and enable a new generation of testing to be performed. Capabilities, open-source software and algorithmic advances in HS and RTHS have developed in parallel with the NEES facilities and research projects (Deierlein et al., 2011)). To demonstrate the progress to date, and to explore the future potential, of HS and RTHS in developing new knowledge related to resilient infrastructure systems, relevant projects published in the NEES Data Repository are discussed herein. The public data repository (https://nees.org/) provides a wealth of information and open data from several HS and RTHS projects, and through these data and metadata the process for the contributions of these projects to civil engineering practice is reconstructed herein .

While advanced sensing technologies and parallel processing have unleashed the real power of cyber-physical systems, earthquake engineering has matured through embracing some innovative cyber-physical techniques. However, to achieve resilient and sustainable communities, a significant change has been taking place across other research areas in structural engineering as well. This change can be accelerated through further implementation and establishment of some powerful cyber-physical techniques, such as HS and RTHS. The structural engineering areas are including, but certainly not limited to, smart structures/infrastructures, advanced energy dissipative systems, structural and operational performance of composite structures subject to wind loads, structural integrity and failure, structural model updating, structural health monitoring, global and local structural performance subject to impact and blast loads, and vulnerability assessment.

Chapter 2

Hybrid simulation in earthquake engineering

The power of HS and RTHS lies in its promise to accelerate the rate at which we can conduct research in earthquake engineering (Shao and Griffith, 2013). In the last decade, an increasing number of researchers have used HS methods as an alternative to quasi-static or shake table testing. Its capability to induce local failure mode analysis under realistic loading and global response evaluation leads this type of test to be more flexible (various conditions, structures, loadings, are possible), without the limitations in size or shape that usually govern shake table tests. Within the NEES network, at least 29 projects have used HS/RTHS to investigate a variety of topics related to seismic engineering (see Fig. 2.1).

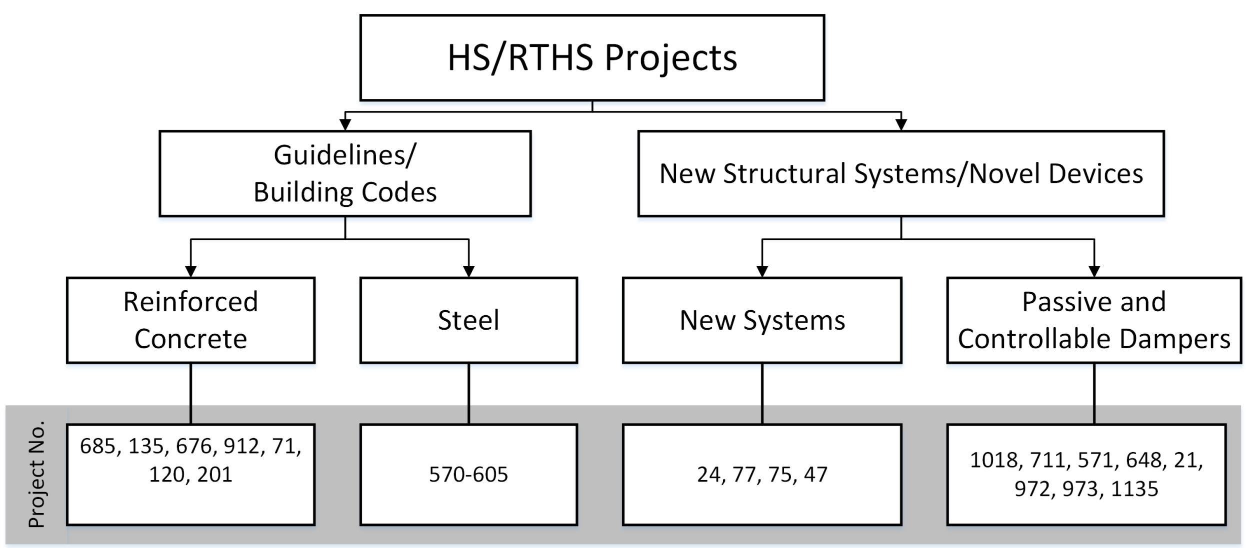


Figure 2.1: Selected HS/RTHS projects in earthquake engineering

Recently, researchers have begun to rely on HS or RTHS to assess local and global responses and compare various aspects related with design guidelines, and specifically with design codes. For purposes of this discussion on the enabling roles, the NEES projects that have used HS or RTHS are categorized in two principal directions: (i) to review, support, oppose, or improve design guidelines in building codes requirements, and (ii) to develop and validate new structural systems or new devices to modify the structural response. A diagram summarizing the primary purpose of using HS for the projects is provided in Fig. 2. In many cases HS was more economical than full scale shake table experiments, and perhaps even the only way to achieve the goals of the projects. Note that all images were provided through the NEEShub at (https://nees.org/) in the respective projects.

2.1 HS for investigating guidelines and codes

In this section, we summarize the progress made using HS in the establishment of guidelines and codes toward the design of infrastructure systems to resist such hazards.

Framework for Development of Hybrid Simulation in an Earthquake Impact Assessment Context (Project 685). This project demonstrated that HS is an economical and efficient technique with many capabilities and applications. In this project, HS provided an innovative way to utilize field measurement data (free-field and structural sensor measurement), combined with system identification, model updating, probabilistic fragility analysis, and earthquake impact assessment packages to evaluate the impact of earthquakes on civil infrastructure in a robust framework. In the proposed framework, free-field measurements were used to define and characterize strong motion records. Structural sensors were used to update the bridge-foundation-soil model. Eight HS and one cyclic test were conducted using 1/25-scale reinforced concrete (RC) pier specimens (see Fig. 2.2). For the HS test, three tests with different hazard levels were conducted by using three synthetic ground motions with peak ground acceleration (PGA) values between 0.2 and 0.9g. Simulation results indicated that the model calibrated with cyclic tests accurately predicts the response in the cases with lower PGA. However, that model underestimates the peak lateral drift response under large PGA, and HS is shown to provide an updated model that yields a more realistic failure probability in fragility functions in the range of high ground motion intensity (Lin et al., 2012). An important deliverable for this project was the development of a tool, NEES Integrated Risk Assessment Framework (NISRAF), that integrates the components of earthquake impact assessment such as structural damage, loss assessment, estimation of nonstructural damage, economic cost, retrofit cost, etc. (Lin et al., 2012). The clear advantage here in using HS is that it provided the capability to perform several inexpensive tests to reach the target structural response, thus creating a family of fragility curves.

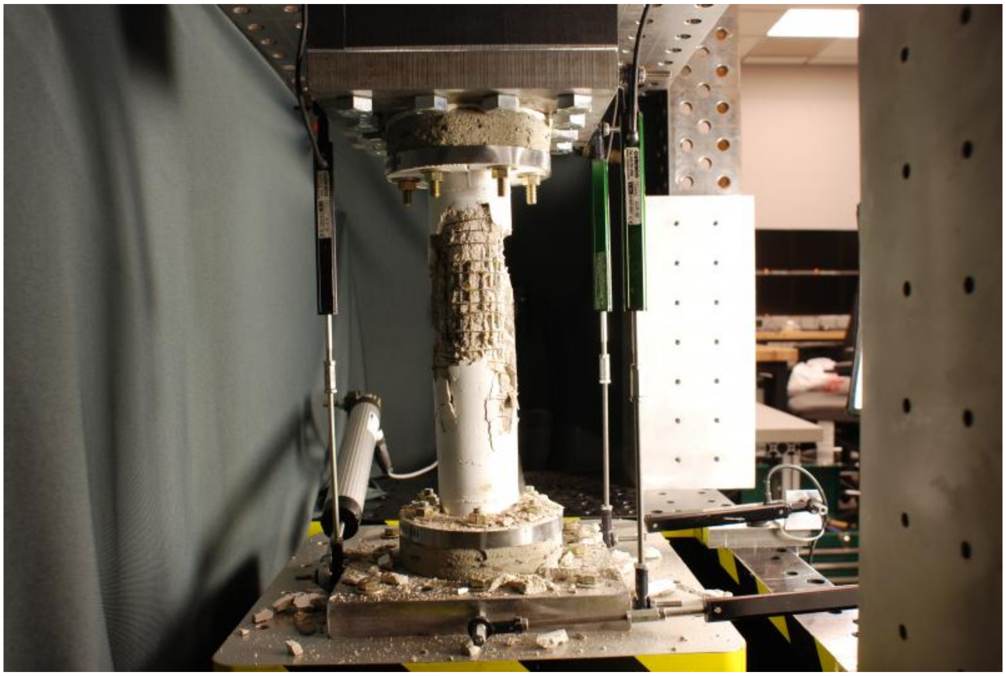


Figure 2.2: Small-scale reinforce concrete pier experimental substructure
(NEES project 685, https://nees.org/warehouse/experiment/3322/project/685)

Hybrid Simulation and Shake-Table Tests on RC Buildings with Masonry Infill Walls (Project 135). One of the objectives of this project was to refine the modeling techniques of hysteretic response and stiffness degradation in elements of RC moment frames interacting with unreinforced masonry (URM) infill walls. The numerical substructure consisted of a 3/4 scale, five-story prototype moment-resisting frame structure designed with its exterior columns as the primary lateral load resisting system. The experimental substructure was the middle bays of the first story (see Fig. 2.3).

Hashemi and Mosalam (2006) concluded that URM infill walls should be included for the design and associated analysis of a structure. The experimental results show that the interaction between the RC frame and the infill wall made the test structure 3.8 times stiffer, reduced the initial natural period by 50%, and affected the structural behavior. Additionally, an increase in the structural damping depends upon the level of displacement. Finally, experimental results showed that the URM infill walls resulted in a 30% increase in the demand on the diaphragm, and directly affected the RC columns at the top and bottom of the infill wall (Hashemi and Mosalam, 2006).

Additionally, a novelty in this project was the comparison between HS and shake table (ST) testing results, which were conducted on a similar test structure with the same sequence of applied ground motions. This comparison revealed that both tests developed a similar cracking pattern and progressive stiffness degradation throughout the two experiments using HS and ST. However, differences between HS and ST experiments for test structure were obtained due to the variation in the damping with amplitude, and the lack of a numerical model able to capture that behavior (Elkhoraibi and Mosalam, 2007)

Figure 2.3: Experimental substructure conformed by RC frame and URM infill in the middle (NEES project 135, https://nees.org/warehouse/experiment/205/project/135

Performance-based Design of Squat Concrete Walls of Conventional and Composite Construction (Project 676). Here researchers performed HS at the Berkeley facility to examine the behavior of squat reinforced concrete structural walls commonly used in nuclear energy plants as a seismic lateral force resisting system. Squat shear walls are those designed with an aspect ratio smaller than 0.5, and are quite thick to provide protection against radiation and fire (Whyte and Stojadinovic, 2012). The experimental substructures were 0.2 m thick, 3 m long and 1.65 m tall shear walls (aspect ratio 0.54, see Fig. 2.4). To simulate the excessive weight of a nuclear power plant, the extra mass was modeled in the numerical substructure and it was adjusted to achieve a 0.14 sec fundamental natural period, which is a realistic value. Various design code procedures were employed to predict the observed responses. In some cases, the recommended methods over predict the peak shear strength of squalls walls by almost a factor of 1.8. However more results would be needed to draw conclusions about the displacement capacities for thick walls. This project demonstrated an efficient use of HS in emulating the huge mass of a nuclear power plant, eliminating the need to use a high capacity shake table.

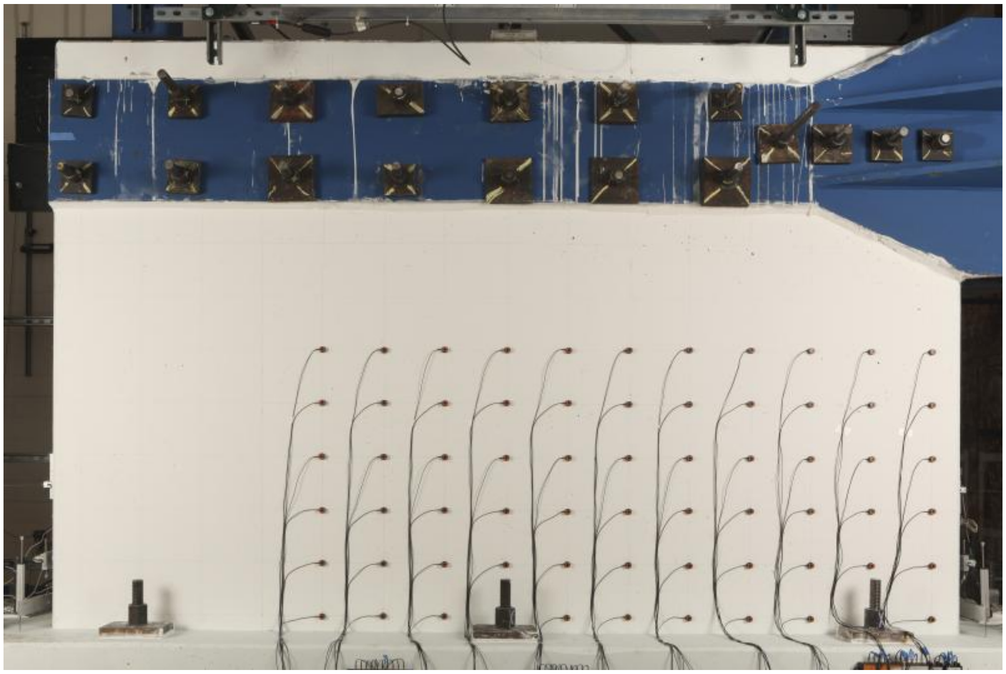


Figure 2.4: RC experimental substructure compose by a thick wall specimen
(NEES project 676, Whyte et al., 2013).

Collapse Simulation of Multi-Story Buildings Through Hybrid Testing (Project 912). In this project, a number of specific test were conducted to predict and evaluate structural collapse responses. A progressive collapse program was conducted to study structural failure using HS as an alternative to earthquake simulators due to the limited capacity of most facilities. Also, the adoption of HS eliminated or alleviated a number of safety concerns associated with a collapsing structure on a shake table. Particularly, a large-scale shake table test was conducted to study collapse in a 2D four-story steel structure (Lignos, 2008). Using a similar frame, several HS were performed to compare the results with the shake table results where only critical components of the structure were tested experimentally with a small number of actuators at the interface of the experimental subassemblies (Hashemi and Mosqueda, 2014b), demonstrating flexibility, cost-effectiveness and safety (see Fig. 2.5).

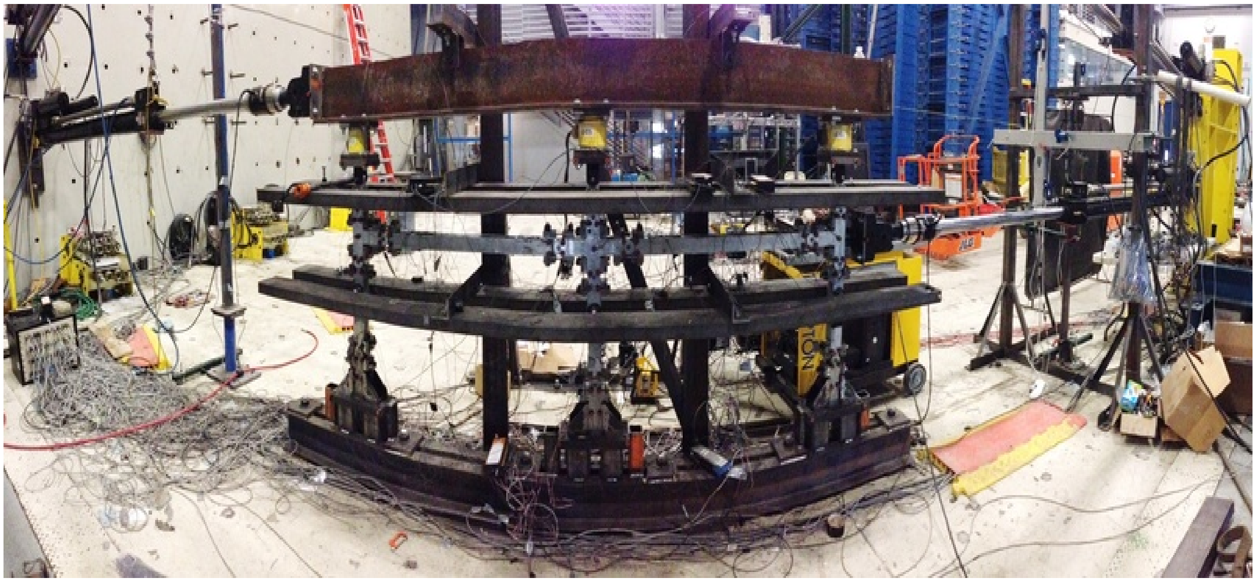


Figure 2.5: Scheme for HS used in collapse test (NEES project 912, Hashemi and Mosqueda, 2014a).

Seismic Simulation and Design of Bridge Columns under Combined Actions, and Implications on System Response (Project 71). To evaluate the impact of spatially-complex earthquake ground motions in bridge piers, an extensive test program was executed to understand the effects of combined demands (vertical and horizontal) that may result in large deformation, excessive structural damage, and structural performance degradation. Two hybrid simulations were performed at the Multi-Axial Full-Scale Sub-Structured Testing and Simulation (MUST-SIM) facility at the University of Illinois at Urbana Champaign. In these hybrid simulations, a pier was constructed as the experimental substructure, and the remainder of the bridge was modeled as the numerical substructure (see Fig. 2.6). In the first HS experiment, the bridge was subject to a horizontal ground motion. In the second HS experiment, the bridge was subject to combination of horizontal and vertical components ground motion (Kim et al., 2011). Because hybrid simulation allowed the research team to reproduce vertical and horizontal components of a ground motion at the same time in a single test, using a component as the specimen, it was unnecessary to perform more resource-intensive tests involving complete structural specimens and a shake table with multiple degrees of freedom.

The shear strength of the piers were evaluated and compared with ACI-318 (2008) and AASHTO (1995). In a first HS experiment, shear capacities calculated using the approximate and refined methods of ACI-318 (2008) were found to be 7% and 4% higher than the shear demand, respectively. In contrast, the shear strength predicted by the AASHTO (1995) was 31% less than the shear demand (Kim et al., 2011). Furthermore, the measured shear demand of the specimen in the second HS experiment was 8% lower than the shear capacity estimated by ACI approach. Researchers concluded that guidelines predicted the shear capacity of the pier in the first experiment conservatively, but in the second experiment, the pier suffered significant damage producing a broadband range for shear capacities calculated with different methods. Combined, horizontal and vertical ground motion in the piers may yield a decrease in shear capacity. Furthermore, neglecting the vertical component of the ground motion in the design procedure can underestimate the consequences of an earthquake in the design of RC bridges.

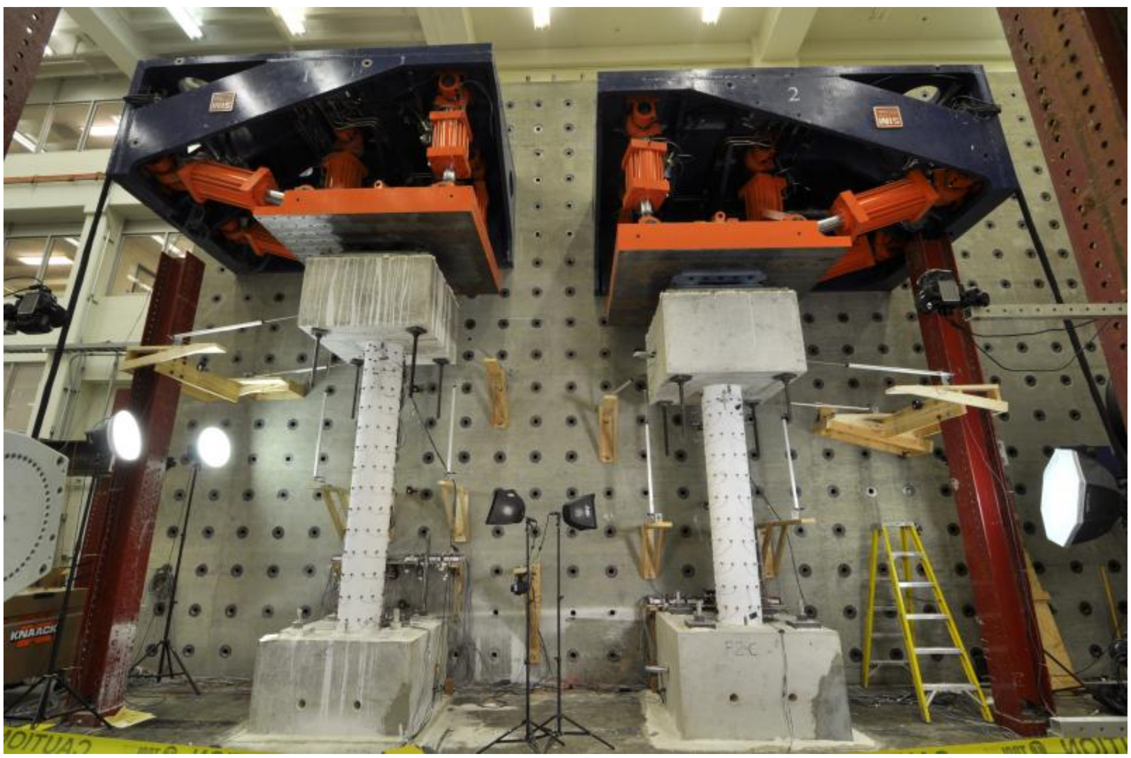


Figure 2.6: Reinforce concrete columns subjected to horizontal and vertical ground motion (NEES project 71, https://nees.org/warehouse/hybrid/4176/project/71).

International Hybrid Simulation of Tomorrow's Braced Frame Systems (Project 605). The objective of this project was to evaluate different bracing configurations and different design strategies intended to improve structural earthquake-resistant systems by increasing the ductility. A series of HS and cyclic tests were conducted using a three-story single-bay concentrically brace steel frames as the experimental substructure to obtain the response of the different buckling restrained brace frames (BRBF) and to investigate the brace-to-gusset connections. The numerical substructure consisted of two five-bay steel moment resisting frames and two one-bay concentrically brace frames in the longitudinal and transversal directions, respectively. As a result of these tests, the researchers recommend using a clearance of three times the thickness of the plate ($3t_p$), unlike the AISC (2010) suggestion of $2t_p$ clearance, to provide an adequate space for welding and allowed enough rotations in the knife plate (Tsai et al., 2013). Also, Lin et al. (2012) proposed a design procedure for BRBF to avoid local failure produced for bulging of steel casing in the buckling restrained brace elements. In this project, HS and RTHS have been also used extensively to evaluate the capabilities of new materials, damping devices, and novel structural systems to improve the seismic response of building and bridges. The use of HS in this project was especially helpful to concentrate on realistic local behavior in the braces examined in a way that is consistent with the global response of the whole structure. Furthermore, flexibility and rapid deployment facilitated a wider variety of tests and configurations.

2.2 HS for establishing novel structural systems

Next we discuss the achievements of several projects that adopted HS or RTHS to demonstrate and evaluate new structural systems.

Behavior of Braced Steel Frames with Innovative Bracing Schemes - A NEES Collaboratory Project (Project 24). The system consisted of a bracing scheme using a suspended zipper frame. Conventional concentrically braced steel frames have the potential to lose stiffness and strength when buckling occurs in the brace, producing undesired vertical forces. In response, a new braced steel frame configuration was developed to meet the objective of providing efficient seismic response. Due to high nonlinearity of brace buckling, HS was conducted to capture the complex chevron brace buckling behavior. Although the zipper frame was not a new idea, the modification proposed here was intended to avoid undesirable deterioration of lateral strength in the frame and resist the potentially significant post-buckling force redistribution, resulting in very strong beams (Leon et al., 2005). In the new concept, the top story bracing members were designed to remain elastic when all the other compression braces buckled and the tension braces and zipper elements yielded. In conducting HS, the experimental substructure, which is scaled to 1/3, represented the first-story braces and consisted of two braces along with the gusset plates connecting the braces to the beam at the top (see Fig. 2.7). The numerical substructure was a FEM model built in OpenSees (OpenSees, 2006). This model used a flexibility-formulation nonlinear bean-column elements with fiber sections for the beams, columns, and zipper columns, and zero-length elements for the connections. A second-order displacement formulation was used to include the nonlinear buckling behavior (Yang et al., 2009). The results of the testing at the Colorado facility indicate that a suspended zipper column can successfully achieve the goal of redistributing the force along the frame height, although large inter-story drifts produced permanent deformation at the first floor. Here, HS was particularly useful in safely capturing the complex responses of the system subject to large deformation and buckling.

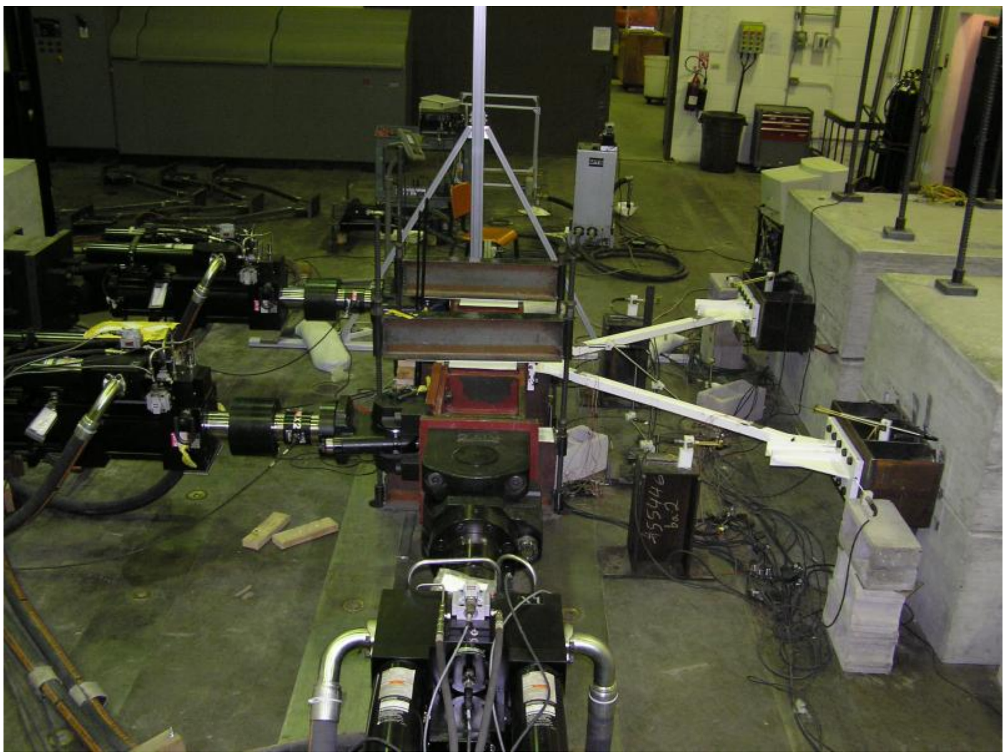


Figure 2.7: Experimental substructure of the suspended-zipper braced frame
(NEES project 24, https://nees.org/warehouse/experiment/110/project/24).

Self-Centering Damage-Free Seismic-Resistant Steel Frame Systems (Project 77). In this project, an innovative structural system was developed to ensure that a moment-resisting frame would be able to survive the design basis earthquake (DBE) without any structural damage. In the design, post-tensioning strands would pre-compress the beams to the columns yielding a passive device with self-centering moment resisting frame (SC-MRF). The system was designed to return to its initial position while dissipating a significant amount energy under large seismic loads. Hybrid simulation was implemented to evaluate a 7-bay, 4-story SC-MRF building designed for a location in the Los Angeles area. The experimental substructure was a 2-bay, 4-story structure scaled to 60% and the remainder of the reference structure was the numerical substructure (Fig. 9).

Using HS, the structure was subjected to four DBE level ground motions, and each lateral floor displacement returned to zero (thus, there were no residual drifts). These experiments demonstrated the system has sufficient performance for Immediate Occupancy (IO) of SC-MRF. Besides, the holes in the beams web dissipate considerable energy under earthquake producing a structure 10% lighter than a traditional welded seismic moment resisting frame W-SMRF (Lin et al., 2013). The HS capabilities enabled a large number of evaluation tests to be performed rapidly and cost-effectively, and with fewer safety concerns.

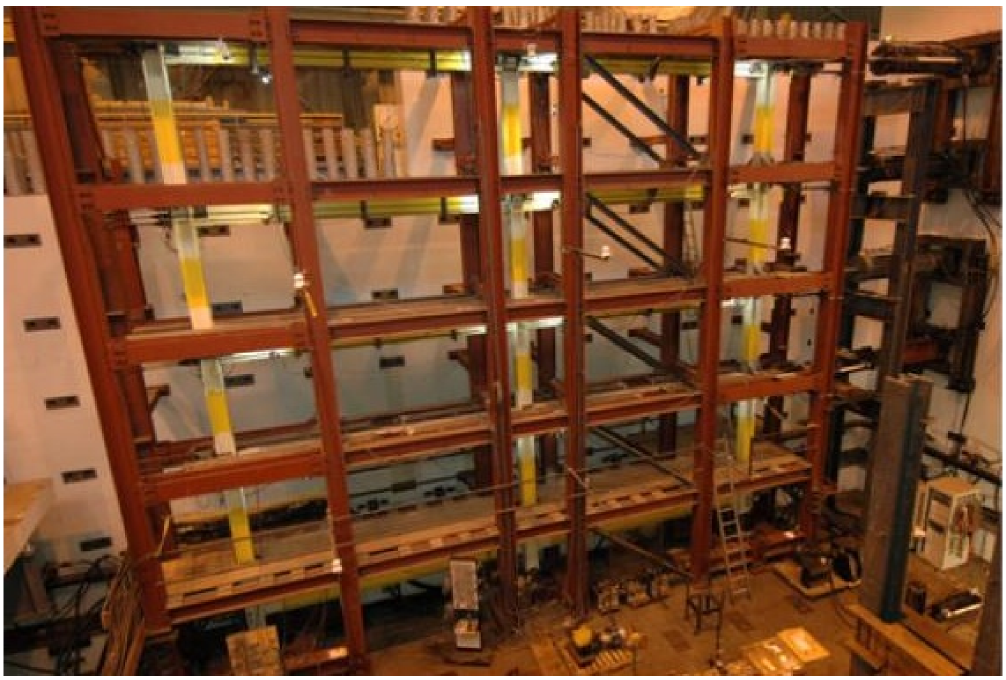
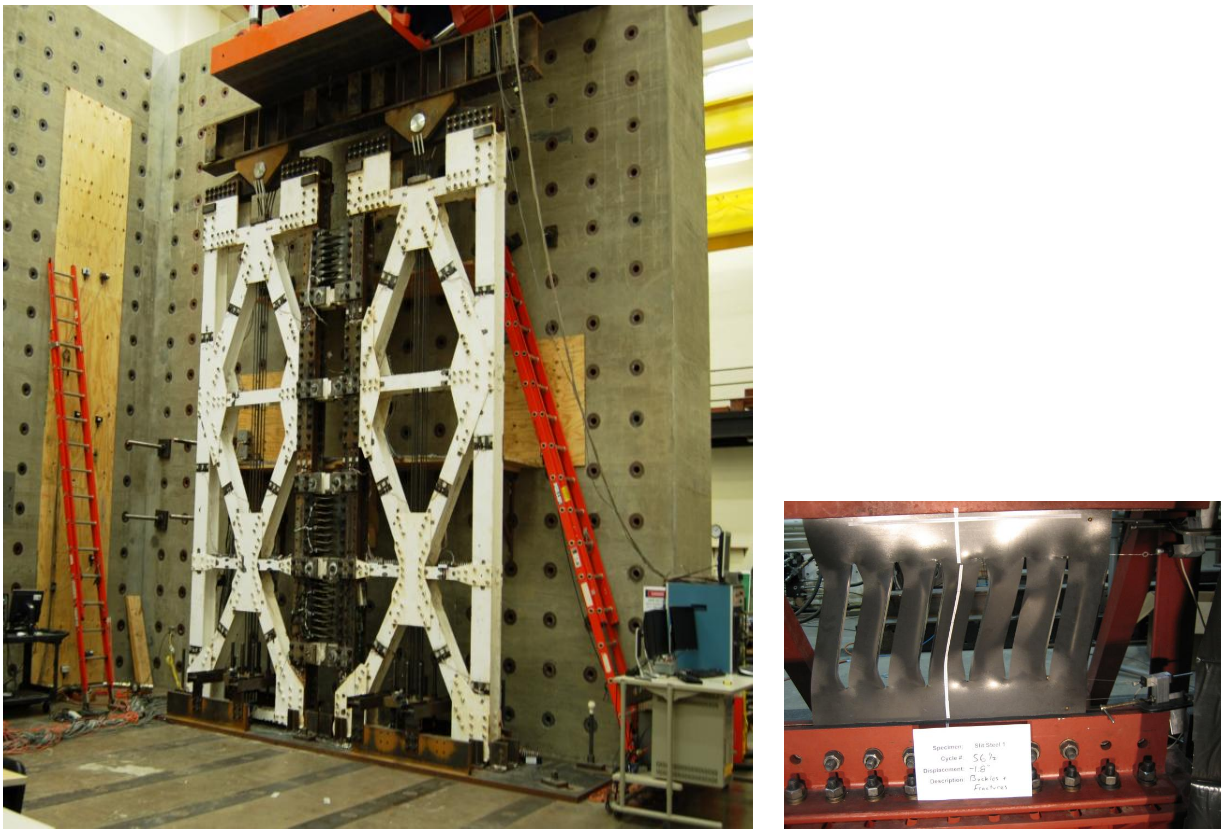


Figure 2.8: SC-MRF 4-story test frame with lateral loading as experimental substructure (NEES project 77, https://nees.org/warehouse/experiment/1151/project/77).

Controlled Rocking of Steel-Framed Buildings (Project 75). A novel passive device was developed and designed to concentrate structural damage in a fuse element intended to be replaced after yielding. The structural system combines three components. The structural steel frames are designed to remain in the elastic range and are allowed to rock at the column base. Vertical post-tensioning strands provide self-centering forces. Fuse elements are used to dissipate energy while yielding. Nine large-scale quasi-static and HS tests were conducted at the University of Illinois at Urbana-Champaign to demonstrate the performance of the controlled rocking system (see Fig. 2.9a). Particularly, HS was used to demonstrate the robustness of the system to remain elastic when were subjected to ground motions, even when drift ratio was approximately 4% without any damage in the braced frame (Deierlein et al., 2005). Since the damage was located in the removable fuses (see Fig. 2.9b), a considerable amount of energy was dissipated (Eatherton et al., 2010).

Here HS played an important role in capturing more realistic global responses of the structure, as well as incorporating its interaction with the fuse elements.



(a) Dual frame configuration specimen

(b) Steel shear plates removable fuse

Figure 2.9: Large-scale test specimen of the controlled self-centering rocking system (NEES project 75, https://nees.org/warehouse/experiments/75).

Innovative Applications of Damage Tolerant Fiber-Reinforced Cementitious Materials for New Earthquake-Resistant Structural Systems and Retrofit of Existing Structures (Project 47). In this project, to enhance the seismic performance of existing steel buildings, a retrofit system was developed and evaluated experimentally. A 1980s steel building design in California was considered for the proposed retrofit. The proposed system consists of high-performance fiber-reinforced concrete (HPFRC) infill panels (see Fig. 2.10) acting as energy dissipation elements that can be easily replaced after a major earthquake. The numerical substructure consisted of a 2-bay, 2-story SMRF building, and the experimental substructure consisted of a 2/3-scale model of 1-bay and 2-stories with 5 double infill panels per story. Hybrid simulation enabled realistic global assessment of the system, and showed that during a DBE the retrofit system reduces seismic demands by approximately 40% in terms of story and residual drift ratios compared with the un-retrofitted frame (Lignos et al., 2014).

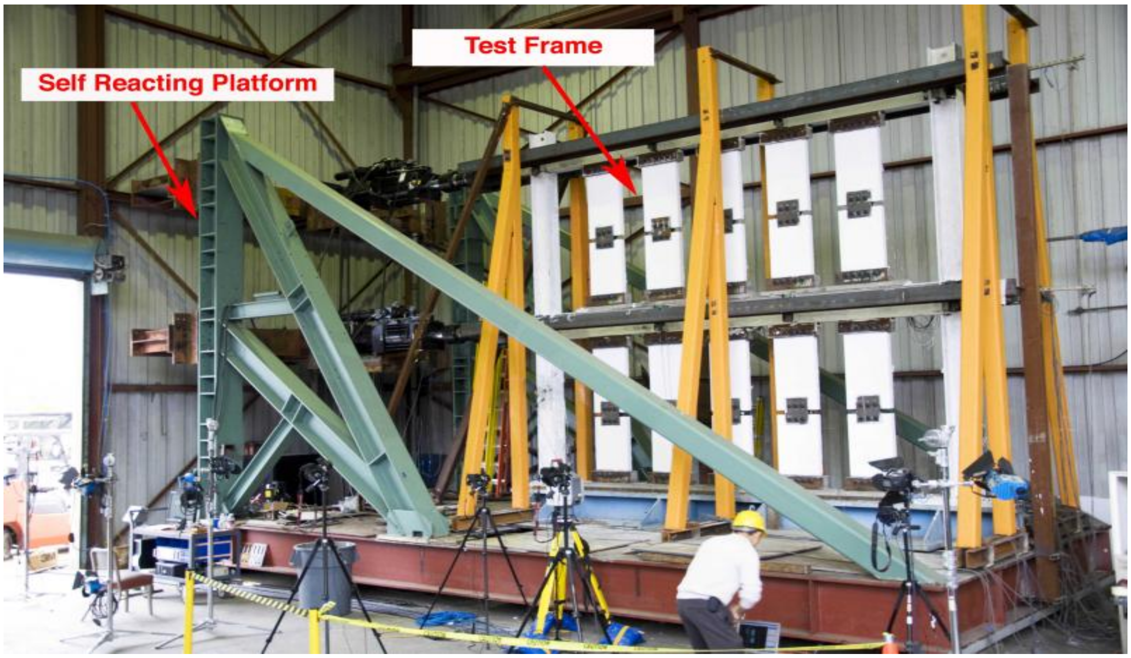


Figure 2.10: Large-scale retrofitted two story moment frame with HPFRC panels (NEES project 47, https://nees.org/warehouse/experiment/72/project/47).

2.3 HS for developing response modification devices

In this section, we showed some projects that used RTHS to get accurate results due to some experimental components exhibit rate dependent behavior, so real-time execution is necessary for accurate results. These control devices can be used to modify the response dissipating energy in civil structures subjected to dynamic loading, such as earthquake, wind and wave excitations.

TIPS - Tools to Facilitate Widespread Use of Isolation and Protective Systems, a NEES/E-Defense Collaboration (Project 571). This collaborative effort between researchers in the U.S and Japan (at E-Defense) focused on creating and promoting tools to facilitate adoption of isolation and protective systems. The existence of such tools was intended to simplify design procedures, disseminate knowledge regarding the use of seismic isolation technology, establish the linkage to building codes, and confirm the impact of such isolators on seismic response of the buildings (Arendt et al., 2010, Ryan et al., 2013). A series of HS were performed using shake tables. A 2-story, 2-bay steel moment frame was the experimental substructure, representing the top two stories of a high rise building. The numerical substructure consisted of the lower portion of the building. The response of the numerical substructure was calculated and used as input to the upper stories (the experimental substructure) mounted on the shake table. The benefits of seismic isolation in such buildings were demonstrated. However, researchers concluded that changes in building codes and guidelines to simplify the use of seismic isolators are necessary. Moreover, these tests would not have been possible at this scale were it not for the HS method and its capacity to obtain specific responses from the experimental substructure to be used as feedback in the numerical analysis, which in this particular case, avoid the necessity of build a high-rise building for the test.

Performance-Based Design for Cost-Effective Seismic Hazard Mitigation in New Buildings Using Supplemental Passive Damper Systems (Project 1018) and ***Advanced Servo-Hydraulic Control and Real-Time Testing of Damped Structures (Project 711)***. More than 170 RTHS were conducted at the Lehigh facility on 3-story steel buildings and 2-story moment resisting frame (MRF) buildings equipped with supplemental passive dampers. Both viscous fluid and elastomeric dampers were considered to assess their impact on the performance of the buildings, and to evaluate and validate the proposed design procedures (Dong et al., 2014). The experimental substructure was scaled to 60% with dampers. The numerical substructure was the remainder of the building. The results showed that when the elastomeric dampers were included in the MRF frame, the base shear was less than the design shear base specified by current specifications producing a structure lighter than a conventional SMRF (Mahvashmohammadi et al., 2013). The researchers concluded that advanced damping systems have strong potential for mitigating the impact of earthquakes on structures and meeting the objectives of performance-based design. However, additional realistic evaluations are a necessary step to increase awareness and encourage their adoption. Even so, the velocity dependent nature of the device and the need for including interactions between the device and frame necessitated the development of advances in RTHS as the test would not have been complete using only quasi-static testing (see Fig. 2.11).

Figure 2.11: large-scale steel structure with viscous dampers (NEES project 1018, Dong et al., 2014).

Semiactive Control of Nonlinear Structures (Project 21), ***Performance-Based Design and Real-Time Large-Scale Testing to Enable Implementation of Advanced Damping Systems (Project 648)***, ***Development of a Real-Time Multi-Site Hybrid Testing Tool for NEES (Project 972)***, ***Development and Validation of a Robust Framework for Real-time Hybrid Testing (Project 1135)***, and ***Real-Time Hybrid Simulation Test-Bed for Structural Systems with Smart Dampers (Project 973)***. Each project produced an important contribution in different subjects. For instance, Project 21 demonstrated the ability of semi-active control devices to improve the structural response subject to earthquake ground motion (see Fig. 2.12). Project 648 conducted the first large-scale RTHS on a complex frame system using multiple actuators. Project 972 developed and demonstrated the capacity of NEES labs to conduct more complex RTHS by involving multiple laboratories and transferring information needed to conduct the test between those locations, which is known as geographically-distributed RTHS. Project 1135 concentrated on the evaluation of new hydraulic actuator control strategies to enable more representative RTHS. Project 973 worked to improve the performance of RTHS for evaluating structures controlled by semi-active devices. This group of NEES projects were among the very first to successfully develop and validate RTHS methods to assess global structural response (Friedman et al., 2013). Initially, RTHS was conducted with a damper alone as the experimental substructure. Additional successes were achieved toward the development of geographically-distributed tests. After advances were made in the actuator controllers, more complex testing was performed using a damped steel MRF as the experimental substructure and RTHS was shown to be successful on a frame structure. Once RTHS methods were developed and demonstrated, they were used to evaluate the global performance of the structures. Shared facilities capable of implementing large-scale RTHS were utilized to develop performance-based design methodologies for advanced damping systems and to develop high fidelity models for devices and improved control algorithms for model-based simulation study. New MR damper control strategies were developed and validated (Friedman et al., 2014). The results indicated that large scale MR dampers could provide significant seismic response reduction even with the maximum credible earthquake (MCE). RTHS was essential to perform these tests as it provides an efficient and cost-effective tool for global evaluation of novel devices, such as MR damper controllers, that exhibit rate dependent behavior making real time execution necessary for accurate results (Phillips et al., 2010).

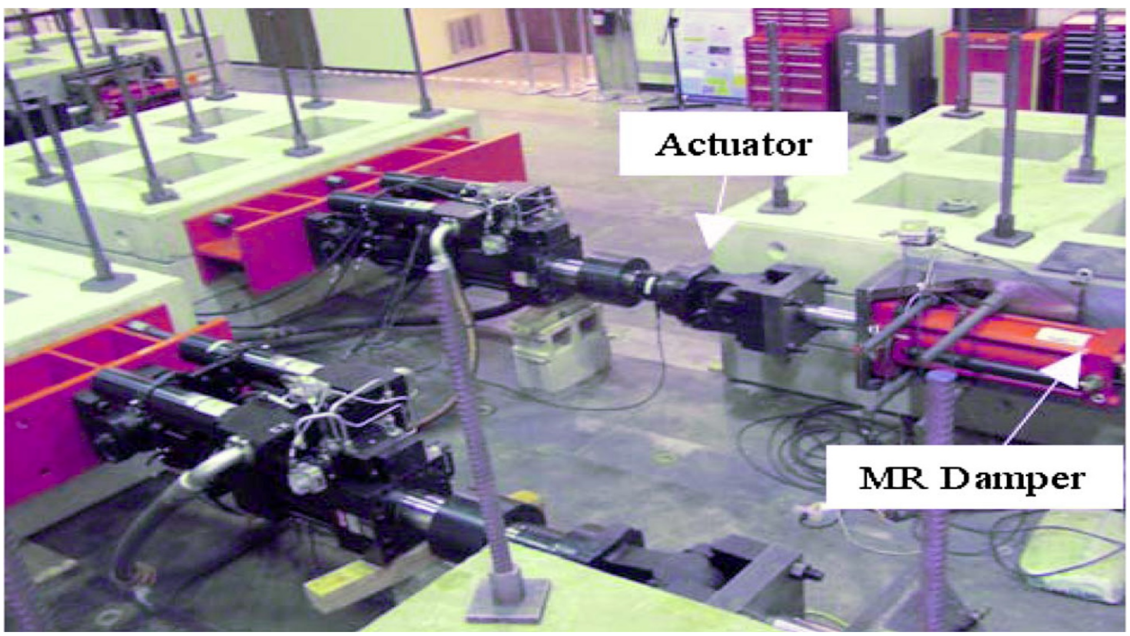


Figure 2.12: Experimental set-up of large scale MR damper at University of Colorado at Boulder (NEES project 21, https://nees.org/warehouse/experiment/664/project/21).

Chapter 3

Concluding remarks

Developing resilient and sustainable communities will require an evolution in the ways that we conduct experiments and perform simulations. Infrastructure system design procedures must be supported by experiments that represent realistic conditions when those structures are in service. The availability of HS and RTHS have clearly expanded the types of testing that is possible to improve resilience and reduce earthquake risk in the built environment. The role of HS in enabling these tests has been exploited to evaluate the performance of new design concepts and structural systems and novel devices, as well as enabling code provisions to be examined with the most realistic loading conditions. The projects revisited and reconstructed through the discussion herein encompass only those projects within the NEES network, providing a broad view albeit still a subset of what is possible using HS/RTHS. Among the projects considered are masonry, reinforced concrete, steel, dampers, bracing systems, and other novel concepts. Together these projects have demonstrated that HS and RTHS provide additional versatility, effectiveness, economy, safety and reliability for reproducing more realistic responses of complex structural and geotechnical systems. Because the numerical substructure can readily be replaced/modified, an unlimited number of structures and configurations can be examined with a single physical specimen. Furthermore, HS and RTHS enable testing of structural configurations that are too tall or too long to be adequately considered in a laboratory, such as long span bridges and high rise buildings. Several of these projects concluded that such advantages were achieved with HS over traditional methods (quasi-static and shake table test). And when a test may be particularly costly or introduce certain safety concerns, HS and RTHS provides alternative approaches in enabling some new earthquake engineering concepts and research to be studied and performed. Note that although HS has promising future, researchers such as those recognized herein are still working toward bringing this technology to the mainstream, and thus making them accessible to a broader set of researchers. A great deal is being learned about employing these methods in new situations to consider system behaviors. Each success leads HS and thus earthquake engineering toward achieving resilience through the examination and validation of novel systems under realistic situations. The possibility of conducting geographically distributed tests, as some of these projects have done, opens new doors to testing complex systems. The capabilities of hybrid simulation continue to be explored in several more projects that are in progress. For updates and details, see: https://nees.org/wiki/RTHSwiki.

Appendix A

Summary of current public NEES HS/RTHS projects

Table A.1: NEES public HS/RTHS projects (December 2014)

ID	Year	NEES project	PI	NEES facility
24	2003	Behavior of Braced Steel Frames With Innovative Bracing Schemes - A NEES Collaboratory Project	Roberto Leon, Jack Moehle, Andrei M. Reinhorn, Benson Shing, Michel Bruneau, Reginald DesRoches	Georgia Institute of Technology, State University of New York at Buffalo, University of California - Berkeley, University of California - San Diego, University of Colorado
4	2004	Real-time Fast Hybrid Testing Steel Frame Test	Eric Staufer	University of Colorado
135	2004	Hybrid Simulation and Shake-Table Tests on RC Buildings With Masonry Infill Walls	Khalid Mosalam	University of California - Berkeley
570 - 605	2004	International Hybrid Simulation of Tomorrow's Braced Frame Systems	Charles Roeder, Dawn Lehman, Stephen Alan Mahin, Taichiro Okazaki	University of California - Berkeley, University of Washington, University of Minnesota, NCREE
21	2005	Semiactive Control of Nonlinear Structures	Richard Christenson	RPI, Texas A&M University, Utah State University, Washington University, University of Colorado at Boulder, University of Connecticut
711	2006	Advanced Servo-Hydraulic Control and Real-Time Testing of Damped Structures	James Michael Ricles	Lehigh University
685	2007	Framework for Development of Hybrid Simulation in an Earthquake Impact Assessment Context	Billie F. Spencer, Amr Elnashai	University of Illinois at Urbana-Champaign

(continued on next page)

ID	Year	NEES project	PI	NEES facility
648	2008	Performance-Based Design and Real-Time Large-Scale Testing to Enable Implementation of Advanced Damping Systems	Shirley Dyke, Anil Kumar Agrawal, Richard Christenson, James Michael Ricles, Billie F. Spencer	Lehigh University, University of Illinois at Urbana-Champaign
972	2009	Development of a Real-Time Multi-Site Hybrid Testing Tool for NEES	Richard Christenson	Lehigh University, University of Illinois at Urbana-Champaign, University of Connecticut
1135	2009	Development and Validation of a Robust Framework for Real-time Hybrid Testing	Shirley Dyke	Purdue University
973	2010	Real-Time Hybrid Simulation Test-Bed for Structural Systems with Smart Dampers	James Ricles	Lehigh University
912	2009	Collapse Simulation of Multi-Story Buildings Through Hybrid Testing	Eduardo Miranda, Ricardo Antonio Medina, Gilberto Mosqueda	State University of New York at Buffalo, University of California, Berkeley
676	2008	Performance-based design of squat concrete walls of conventional and composite construction	Andrew Whittaker, Laura Nicole Lowes, Bozidar Stojadinovic	State University of New York at Buffalo, University of California, Berkeley
77	2005	Self-Centering Damage-Free Seismic-Resistant Steel Frame Systems	Richard Sause, James Michael Ricles	Lehigh University, Princeton University, Purdue University, NCREE
–	2001	Fast hybrid test platform for seismic performance evaluation of structural systems	Benson Shing	University of Colorado
1084	2012	Near Collapse Performance of Existing Reinforced Concrete Frame Buildings	Mehrdad Sasani, Xiaoyun Shao	University of Illinois at Urbana-Champaign

(continued on next page)

ID	Year	NEES project	PI	NEES facility
–	2011	EAGER: Next Generation Hybrid Simulation, Evaluation and Theory	Khalid M. Mosalam	University of California, Berkeley
934	2010	NEESsoft-Seismic Risk Reduction for Soft-Story, Wood Frame Buildings	John Willem van de Lindt, Mikhail Gershfeld, WeiChiang Pang, Xiaoyun Shao, Michael Symans	State University of New York at Buffalo, University of California, San Diego, University of Alabama
75	2005	Controlled Rocking of Steel-Framed Buildings	Gregory Deierlein, Sarah Billington, Jerome Hajjar	University of Illinois at Urbana-Champaign, Stanford University, Hyogo Earthquake Engineering Research Center (E-Defense)
707	2008	Rapid Return to Occupancy in Unbraced Steel Frames	Peter Dusicka, Jeffrey Berman	Portland State University, University of California, Berkeley
1085	2011	Seismic Rehabilitation of Substandard Building Structures through Implementation of Stiff Rocking Cores	Michael Pollino, Gilberto Mosqueda, Bing Qu	State University of New York at Buffalo
120	2004	The Multi-Site Soil-Structure-Foundation Interaction Test (MISST): LEHIgh	James Ricles	Lehigh University, San Diego Supercomputer Center
201	2006	The Multi-Site Soil-Structure-Foundation Interaction Test (MISST): Illinois	Billie F. Spencer	University of Illinois at Urbana-Champaign
71	2005	Seismic Simulation and Design of Bridge Columns under Combined Actions, and Implications on System Response	David Sanders, Abdeldjelil Belarbi, Shirley Dyke, Amr Elnashai, Pedro Silva, Jian Zhang	University of Illinois at Urbana-Champaign, Missouri University of Science and Technology, University of Nevada-Reno

(continued on next page)

ID	Year	NEES project	PI	NEES facility
922	2010	Post-Tensioned Coupled Shear Wall Systems	Yahya C Kurama, Michael J McGinnis	Lehigh University
1018	2009	Performance-Based Design for Cost-Effective Seismic Hazard Mitigation in New Buildings Using Supplemental Passive Damper Systems	Richard Sause, James Michael Ricles	Lehigh University
571	2007	TIPS - Tools to Facilitate Widespread Use of Isolation and Protective Systems, a NEES/E-Defense Collaboration	Keri L Ryan, Stephen Alan Mahin, Gilberto Mosqueda	State University of New York at Buffalo, University of California, Berkeley, Hyogo Earthquake Engineering Research Center (E-Defense),
47	2005	Innovative Applications of Damage Tolerant Fiber-Reinforced Cementitious Materials for New Earthquake-Resistant Structural Systems and Retrofit of Existing Structures	James Wight, Sarah Billington, Sherif El-Tawil, Gustavo Jose Parra-Montesinos	University of Michigan, Stanford University, University of California, Berkeley
1235	2008	Real-time Hybrid Simulation Method and Technique for Dynamic Damage Process Analysis of Large-scale Building and Bridge Structures	Bin Wu, Yan Xiao	Harbin Institute of Technology

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